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Was There a Late Time Phase Transition in the Early Universe?

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Abstract

The Universe may have undergone a vacuum phase transition subsequent to the decoupling of the microwave background radiation with matter. Under certain circumstances "soft" cosmic topological defects can form, such as domain walls, which can lead to the formation of large scale structure. Since these structures form after decoupling, the constraint imposed by the observationally small anisotropy of the microwave background radiation, $\delta T/T \lesssim 10^{-5}$, is weakened. A soft-defect scenario is a novel alternative to both cosmic string and to inflation-produced quantum fluctuations as the origin of structure in the Universe.

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The problem of generating structure (galaxies, clusters, voids, stars, people, etc.) in a universe that appears very homogeneous and isotropic on the largest distance scales and earliest times is, perhaps, the central problem in cosmology today. The difficulty faced by any proposed mechanism owes to the constraint on the initial "lumpiness" of the universe from the observed smoothness of the $3^o K$ microwave background radiation. This radiation, a relic of the big-bang, last interacted with matter at a redshift of about $z \sim 10^3$, and shows a surprising uniformity in temperature with fluctuations bounded by as little as $\delta T/T \leq 2 \times 10^{-5}$ on some angular scales.[1] The lumpiness of the universe at this time is bounded as well since pre-existing density fluctuations would have differentially red- and blue-shifted the background radiation giving rise to observable temperature fluctuations. It is well known that small initial density fluctuations, $\delta\rho/\rho << 1$ can only grow linearly with the cosmological expansion, $[(\delta\rho/\rho)_{today} \propto (1+z)(\delta\rho/\rho)_{redshift\ z}]$, due to gravitation. How, then, did the enormous density contrasts observed today grow in the period of $\sim 10^3$ redshifts, given that the current $\delta T/T$ limits seem to imply $(\delta\rho/\rho)_{z\sim 10^3} \lesssim 10^{-4}$ at decoupling?[2]

Once the density fluctuations are of order unity, they grow very rapidly and can produce the contrasts seen, for example, in comparing the density of a star to the average density of matter in the universe, $\rho_{star}/\rho_{ambient} \sim 10^{28}$. If linear growth started at decoupling, then $(\delta\rho/\rho)_{today}$ is $\lesssim 0.1$, implying that we would have never attained nonlinear growth. On the other hand, if there is non-baryonic dark matter (*e.g.*, axions), growth could start when $\rho_{matter} \sim \rho_{radiation}$ at $z \sim 10^4$, which might produce the start of non-linear growth at $z \sim 1$. This may seem to be marginal, yet one might argue that the spectrum of initial density fluctuations contains a small probability of having few large fluctuations that can ultimately lead to the formation of the observed structure. However, from the existence of quasars and galaxies at large redshifts we see that well formed structure already exists at $z \sim 4$. Furthermore, there appears to be a large scale coherent streaming motion of galaxies[3] on a scale of $R \sim 50$ *to* 100 Mpc, suggesting the existence of exceedingly massive objects. Such objects are very difficult to form in most models given the present limits on $\delta T/T$. If further observations ultimately yield a tightening of the limit on $\delta T/T$, the situation will become even more constrained.

Previous proposals for the formation of large-scale structure have relied upon generating density fluctuations at a very early cosmological epoch (e.g., the Grand Unified [GUT] epoch when $kT \sim 10^{14}$ GeV) which survive to serve as seeds at the galaxy formation epoch at $kT \sim 10^{-2}$ eV. These include quantum mechanical Gaussian fluctuations produced during inflation[4] and topological defects such as cosmic strings[5]. In some scenarios these seeds gravitationally accrete large quantities of non-baryonic dark matter, whereas in others they explode and push the baryons about[6]. We will not go into a detailed commentary on each of these models, noting only that the aforementioned combination of observations has been difficult (but maybe not impossible) for any existing model to satisfy.

The purpose of this article is to review and update a completely novel, if not radical, proposal[7] in which energy density fluctuations are generated *after* decoupling.[8] This implies *a priori* a minimal imprinting of the induced structure upon the microwave background radiation, *i.e.*, a relatively small induced $\delta T/T$ for any given produced structure. The fluctuations here are associated with "soft" topological structures, typically in the form of domain walls (though this is not the only possibility) having small internal energy densities. The domain walls are kink-solitons; that is, topologically stable solutions to the equations of motion for some very weakly interacting scalar field, ϕ. In the models considered the mass of the ϕ particles m_ϕ is so small that the thickness of the kink, given by the Compton wavelength, $\hbar/m_\phi c$, is a cosmological distance scale. The original motivation for expecting such low-mass particles and a late-time phase transition came from a study of the possible pseudo-Goldstone bosons which arise quite naturally in a variety of GUT settings. Pseudo-Goldstone bosons, such as massless familons[9], occur when the pattern of masses of the observed fermions is associated with a spontaneously broken, continuous, global (ungauged), symmetry. With further small explicit breakings of these symmetries, familons acquire minuscule masses, *e.g.*, in the "schizon" models[10] these are typically of order $m_\phi \sim m_f^2/f_\phi$, where $f_\phi \sim 10^{14}$ GeV to 10^{16} GeV is a generic grand unification scale, and m_f the mass of the associated family of fermions.

In ref.[7] a specific particle-physics based model was considered which postulated the existence of such schizons in association with the neutrinos. This tied the central density of a domain wall to the mass of a neutrino, m_ν, and the thickness of the wall to both m_ν and a grand-unification scale f_ϕ. For $f_\phi \sim 10^{15}$ GeV and m_ν in the range 1.0 to 0.01 eV, the ratio of wall density to the ambient density of matter will then become greater than unity at a redshift of $z \sim 100$. For the above parameters the thickness of the wall will be in a range of 10 to 10^5 parsecs. The phase transition sketched out in ref.[7] is fundamentally no different than those invoked in inflationary schemes. The key idea is that new physics is introduced here involving phenomena of extremely low energies, and much of what we say is generic to any late-time phase transition. Indeed, it is interesting to explore further the possible connections with particle physics that harbor such phenomena.

In the remainder of this discussion we will simply treat the domain walls as phenomenological objects having characteristic thicknesses, δ, and mass per unit area, σ, (for the original model of ref.[7], $\delta \sim f_\phi/m_\nu^2$ and $\sigma \sim m_\nu^4\delta \sim m_\nu^2 f_\phi$). The walls form during a phase transition at a redshift z_0. In addition we define R as the typical correlation scale for structures in the domain wall network. At the time of the phase transition, the walls are randomly distributed and typically contiguous or intersecting, with the average spacing between walls, r_0, of order $r_0 \sim \delta$ to $r_0 \sim H^{-1}$ depending upon the model. As the Universe expands and cools the system relaxes, and individual walls become well-defined kink-soliton configurations. The spacing between walls grows and becomes $r_0(1+z_0)/(1+z)$ at a redshift $z < z_0$. In addition, there will be slow recombination of structures as well as other evolutionary effects. The domain wall network is expected to contain both closed surface walls (dubbed "vacuum bags") and infinite walls.

Ultimately one expects infinite cosmic domain walls to become flat on the scale of the horizon. If the walls have a large central energy density then they give rise to unacceptably large distortions in the microwave background and Hubble flow; this is the "usual" cosmic domain wall disaster and was first noted by Zel'dovich *et. al.*[11] In the case of soft walls, the central energy densities are very low and the large domain walls suggest an intriguing mechanism that may account for the large-scale streaming motion in a natural way[12] as we shall describe below. It is furthermore expected that small local structures, *e.g.*, vacuum bags which are spherical bubbles whose walls are the kink-soliton will form and become, ultimately, the nucleation sites for galaxies, *etc.* Several groups[13,14,15] are now actively analyzing the details of this scenario, *e.g.*, behavior of vacuum bags, the evolution of domain wall networks, and the distribution of observable structures expected in the model.

The evolution of the walls and vacuum bags is quite complicated as there are potentially a very large number of processes that can come into play. The stress-energy of a wall consists of a surface-energy density and a surface-tension *of equal magnitude.* This surface tension causes vacuum bags to collapse and small-scale irregularities on infinite walls oscillate. In either case the walls lose energy via ϕ-particle and gravitational radiation. In addition, if there is a background density of some other particles that interact with ϕ (*e.g.*, neutrinos) then it will exert a force that will tend to damp any motion of a wall relative to the cosmic rest frame.

Press, Ryden and Spergel[13] have completed a preliminary analysis of the evolution of a domain-wall network. They find that the network quickly becomes dominated by infinite walls that are flat on scales of order the horizon and that small local structures quickly disappear. We note however that their numerical code may lack the resolution necessary to track the ultimate fate of the vacuum bags, a problem which is most important when the scalar potential has multiple minima as in the (theoretically favored[7,10,14]) sine-Gordon case. From the point of view of structure formation, the fate of vacuum bags is the most interesting question. It is important to note, moreover, that the evolution depends crucially upon the underlying effective theory of the field which produces the domain wall kinks. In a theory with a potential of the form:

$$V(\phi) = \lambda(v^2 - \phi^2)^2 \qquad (1)$$

i.e.

a "double-well" potential, the walls tend to "intercommute," undergoing a rearrangement upon interacting, and dissipating energy in the form of free ϕ, and some gravitational, radiation. Vacuum bags in these models shrink down to blobs that eventually disperse into free particles.[13,14] Left behind are very large walls which stretch across the entire universe. Naively, if such structures are related to galaxy formation scenarios (thereby requiring $\rho_{wall}/\rho \gtrsim 10^{-4}$) then they would lead to a large $\delta T/T$ in conflict with observations. We view this as a less interesting scheme. However, if the model is of the "sine-Gordon" type, with:

$$V(\phi) = m^4 \sin(\phi/f) \tag{2}$$

as always occurs in pseudo-Goldstone boson theories, then there are remarkable stability constraints on the kink-solitons: two opposing, flat kinks in a collision are transparent and will pass through one another. This implies that domain walls tend not to intercommute, unless they have large curvature, and leads moreover to a striking behavior for vacuum bags, recently demonstrated by Widrow[14]. A spherical vacuum bag will collapse and undergo a "bounce"; in this process a small fraction of the energy is lost to radiation. Typically the vacuum bag reexpands and continues to recollapse for many iterations until finally only a dissipative blob, or even a black hole, remains. The stability of the vacuum bag can no doubt be enhanced by endowing it with anisotropies, inhomogenieties, angular momentum, *etc.*

We should further point out that the flat infinite domain wall can be, in principle, avoided by making all domain walls unstable, as occurs in various incarnations of the models discussed above. Consider for example the superposition of sine-Gordon potentials with multiple non-degenerate minima:

$$V(\phi) = m_1^4 \sin(n_1\phi/f) + m_2^4 \sin(n_2\phi/f) \tag{3}$$

where $n_1 < n_2$ are integers. If n_2/n_1 is noninteger, we expect domain walls to occur, but one side will be a region of false vacuum having higher vacuum energy than the true vacuum on the other side of the wall. Regions of false vacuum shrink due to vacuum pressure, and all walls eventually disappear. However, the density fluctuations may persist sufficiently to drive structure formation. This alternative has not been explored in detail.

The bounce behavior of vacuum bags is important, since a vacuum bag with $\rho_{bag}/\rho > 1$ (irrespective of whether it contains true or false vacuum) persisting for a Hubble time can drive the nonlinear accretion of the surrounding matter. Moreover, a highly anisotropic bag would be expected to develop self–intersecting points of large curvature which are expected to lead to "fission" into smaller vacuum bags, etc. Thus, a parenting process for the formation of local clusters of galaxies can be envisioned here in which the matter ultimately accretes onto the remaining small vacuum bags in a neighborhood defined by the large parent structure. Simulations of the evolution of complex vacuum bags have not yet been carried out, but work is in progress. In the numerical simulations of both Press *et al.* [13], and Widrow[14], only surface tension and ϕ radiation are taken into account. The motivation for this is both simplicity and the belief that gravitational radiation and particle–wall interactions are negligible for the models of interest. Still, these other processes should be investigated in more detail.

Flat cosmic domain walls, owing to the presence of internal pressure as well as energy density, actually gravitationally *repel* matter.[16] On the contrary, spherical vacuum bags have net vanishing pressure and positive mass as seen from outside at distances greater than the radii of the bubbles, and will attract matter. Accreting vacuum bags lead to subsequent evolution of the conventional matter with collapse times that are much more rapid than standard linear growth. Furthermore, the energy within a vacuum bag at the end of its history could mimic the effects of dark matter. In the central core of a collapsing bag the energy density is of order $\sigma(R_0^2/\delta^3)$ where R_0 is the initial radius of the bag. Here, all of the initial surface energy in the bag has been localized into a region of radius $\sim \delta$. One can even form a black hole if the Schwarzschild criterion is satisfied.[14]

The flat, repulsive walls may actually help explain certain puzzling cosmological observations, as envisioned by Stebbins and Turner[12]. As mentioned above, a remarkable coherent streaming motion of all local galaxies within a region ~100 Mpc has been observed[3] which is extremely difficult to explain in conventional scenarios. It has been proposed that a "Great Attractor,"[17] a super-super–cluster of order $10^{17}M_{\odot}$, in the general direction of Hydra–Centaurus may be required. However, in ref.[12] it was suggested that this could arise from the great domain wall stretching across our present Hubble volume. Moreover, the arguments of Stebbins and Turner can be used to place a limit on the fraction of critical density in the ϕ field today, Ω_ϕ, due to the induced large scale velocities. From the present data[3] on $R \sim 40$ Mpc we know that $\Omega_\phi(1+z_0)\delta\rho/\rho \lesssim 0.2$, where z_0 is the redshift of the phase transition and $\delta\rho/\rho$ is the density variation in the ϕ field. Thus, for $\delta\rho/\rho \sim 1$ we have $\Omega_\phi \lesssim 0.2/(1+z_0)$. This constraint sets bounds on the evolution of the ϕ field structures.

The fluctuations in the microwave background for a late–time model will usually be dominated by the effect of the propagation of the background through the gravitational field set up by the moving wall network. One finds:

$$\frac{\delta T}{T} \sim \left(1+\frac{\gamma v}{c}\right) G\sigma R \tag{4}$$

where v is the velocity of the structure, γ is the relativistic factor and G is Newton's constant. For vacuum bags $R \sim \delta$ and $\gamma \sim 1$ so the approximate result of reference [7] is obtained. Note that $\delta T/T$ increases with R to the maximum structures produced. Therefore $\delta T/T$ rises with angular size θ until encompassing the maximum scale R, and then remains flat for larger θ. For sufficiently small σ the above expression for $\delta T/T$ is supplanted by the Rees-Sciama[18] effect from the observed structure, but such values of σ are unlikely to generate structure. In general, the walls are massive enough that $v/c \leq 1$, and $\gamma \sim 1$. If evolution leads to a few dominant walls then $R \sim R_H$ and the large $\delta T/T$ problem arises as described by Press *et al.* [13] or possibly a situation similar to the one considered by Stebbins and Turner[12] might arise.

Multiple minima or non–degenerate minima with decaying domain walls can lead to $R \leq R_H$. If there exists an observable structure of size R then late–time walls will tend to produce the minimum $\delta T/T$ consistent with such a structure. However. if evolution implies even larger structures as in ref.[13] one can encounter limiting constraints. Thus, scenarios which lead to $R \leq 100$ Mpc are preferred. Note that if vacuum bags are produced then the structure they seed can be independent of the large wall structure in which case σ can be reduced sufficiently to even enable $G\sigma R_H$ to be consistent with $\delta T/T$. For the original model of ref.[7] with R arbitrary (instead of $R \sim \delta$) we obtain:

$$\frac{\delta T}{T} \sim \frac{m_\nu^2}{M_{Planck}} f_\phi R \sim 2 \times 10^{-6} \left(\frac{m_\nu}{10^{-2} ev}\right)^2 \left(\frac{f_\phi}{10^{15} GeV}\right) \left(\frac{R}{10\ Mpc}\right) \tag{5}$$

which could easily accomodate structures of $R \sim 100$ Mpc for reasonable parameter values.

Tests for the model vary with the specific details. The mechanism of ref.[7] requires a generic pseudo–Goldstone boson which will be hard to detect directly, but its brethren associated with charged leptons or quarks produce potentially observable new phenomena, e.g., new composition dependent pseudo–Gravitational forces, as detailed in ref. [10]. The observation of such effects and non–zero neutrino masses would be compelling circumstantial evidence for possible cosmological effects proposed here.

The recent observations[19] of an excess at sub–millimeter wavelengths in the microwave background, if real, may also be explained with the help of a late–time phase transition. In particular, this non–linear growth model may be the only way to have significant star formation at $z \gtrsim 30$. Hogan, et.al.[20] argue that such star formation could create the necessary ionization. It should also be noted that energy released by the phase transition itself or by decay or annihilation of topological defects might provide an alternate source for ionization.

Obviously much work remains to be done to examine the details of this class of models. In particular, the astrophysics of the detailed large scale structure that is generated by such late time fluctuations is only sketched here; and full hydrodynamic calculations will have to be carried out. Furthermore, detailed particle physics models will have to be developed to see if all the preferred properties really exist in a fully consistent model. Eventually we would hope to make detailed quantitative predictions about the model vis-à-vis large scale structure. However, the present large scale structure observations are still quite qualitative. Quantitative statistical measures have yet to definitively describe the apparent structure in a reproducible manner. Anecdotally, voids, filaments, sheets, bubbles or sponges appear[21], depending on the analyses used and on the rapporteur. Conceivably cosmic membranes could make any or all of these structures depending on how they evolve. Hopefully, specific quantitative predictions will be made before the observational data converge. Our purpose here is to alert readers to the fact that an alternative to the standard galaxy formation scenarios may exist. The physics it relies upon is not any more exotic than the GUT physics that the standard scenarios utilize. At low energy scales the model might even be testable in the laboratory. In any case, it may be the only model that can survive possible eventual limits of order $\delta T/T \lesssim 10^{-6}$.

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